Quantitative Characterization of Impacts of Coupled Geomechanics and Flow on Safe and Permanent Geological Storage of CO_2 in Fractured Reservoirs

Project Number DE-FE0023305

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U.S. Department of Energy

National Energy Technology Laboratory
DE-FOA0001037 Kickoff Meeting

November 12-13, 2014

Presentation Outline

- Benefit to the Program
- Project Overview
- Methodology - Laboratory Studies
- Methodology - Simulation
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- Organization Chart
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Benefit to the Program

- Evaluate and predict: storage capacity of fractured reservoirs; leakage potential along faults or fractures that intersect a sealing formation; reservoir and sealing formation behavior under pressure from injected CO2

- Benefits: improve ability to predict geologic storage capacity within ±30 percent; improve reservoir utilization by understanding how faults and fractures affect the flow of CO2; ensure CO2 storage permanence

Project Overview: Goals and Objectives

- Develop understanding of injection pressure induced geomechanical effects on CO_2 storage systems, including rock deformation and fracturing processes

- Model CO_2-injection induced rock mechanical processes associated with CO_2 storage in reservoirs to quantify flow, storage, and potential leakage pathways as well as remediation measures

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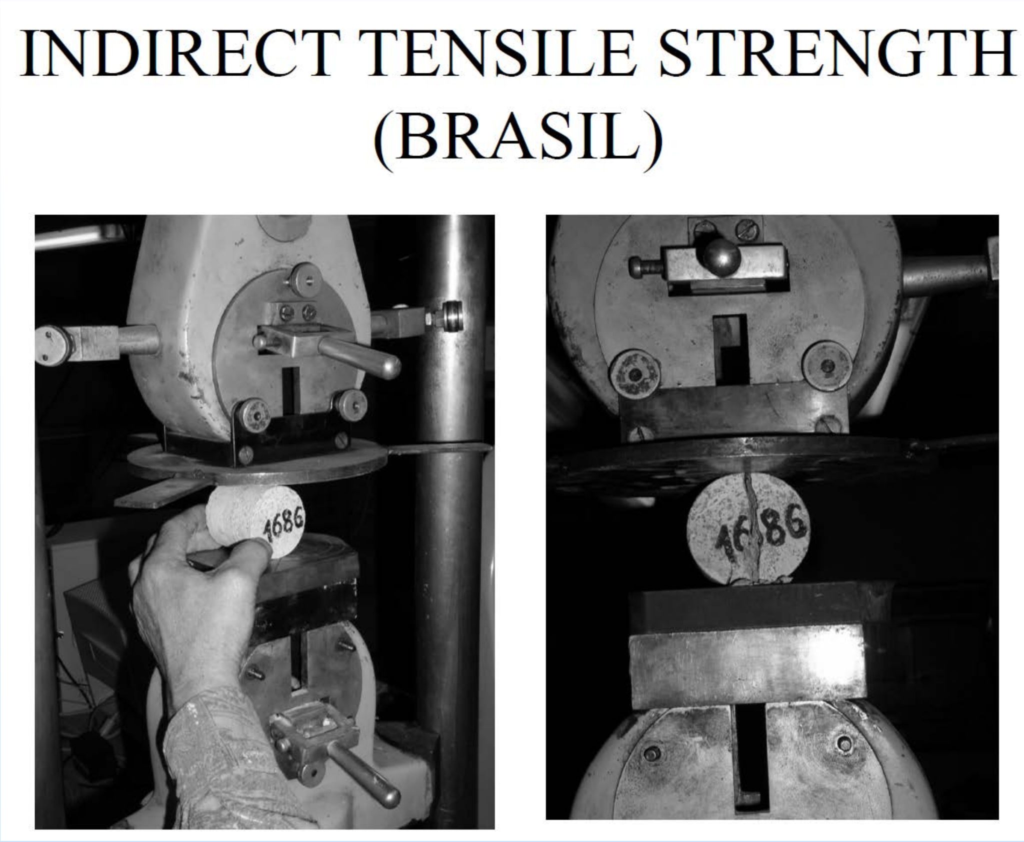
Methodology, Laboratory Studies

- Create Fracture Aperture
- X-ray CT Scan of Rock
- Permeability Measurement
- Triaxial Test

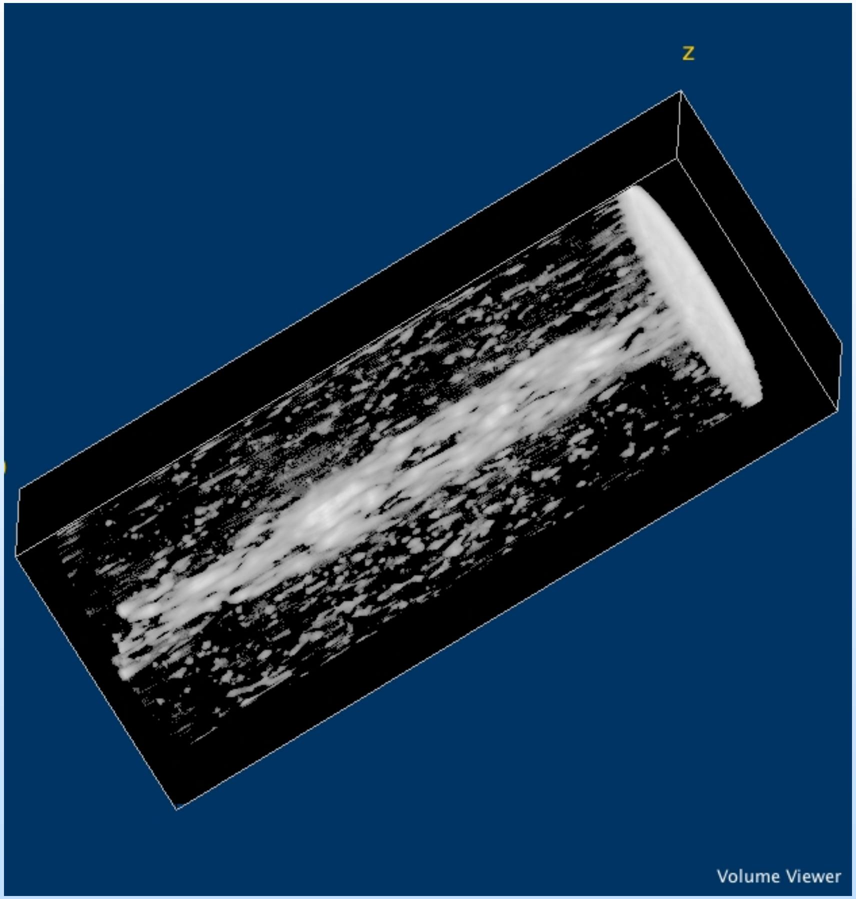
Create Fracture Aperture

- Brazilian method
- Splits core perpendicular to bedding
- Forms two semi-cylindrical halves
- Reassemble halves with thin shims to create an aperture



X-ray CT Scan of Rock

- Tomography – imaging by sections using penetrating wave
- X-rays produce images of rock slices
- Slices reassembled to obtain 3D image of rock
- CT scan of fractured core showing aperture



Permeability Measurement

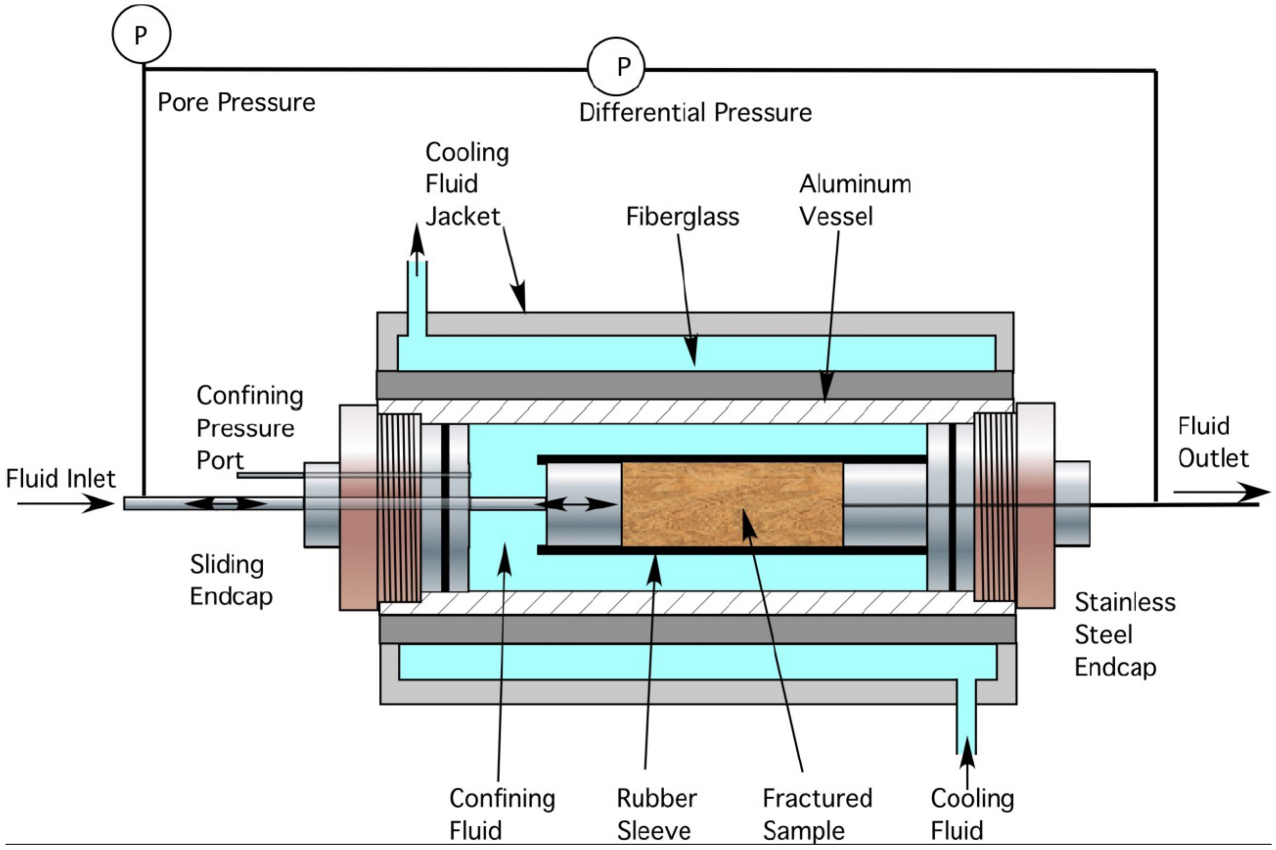


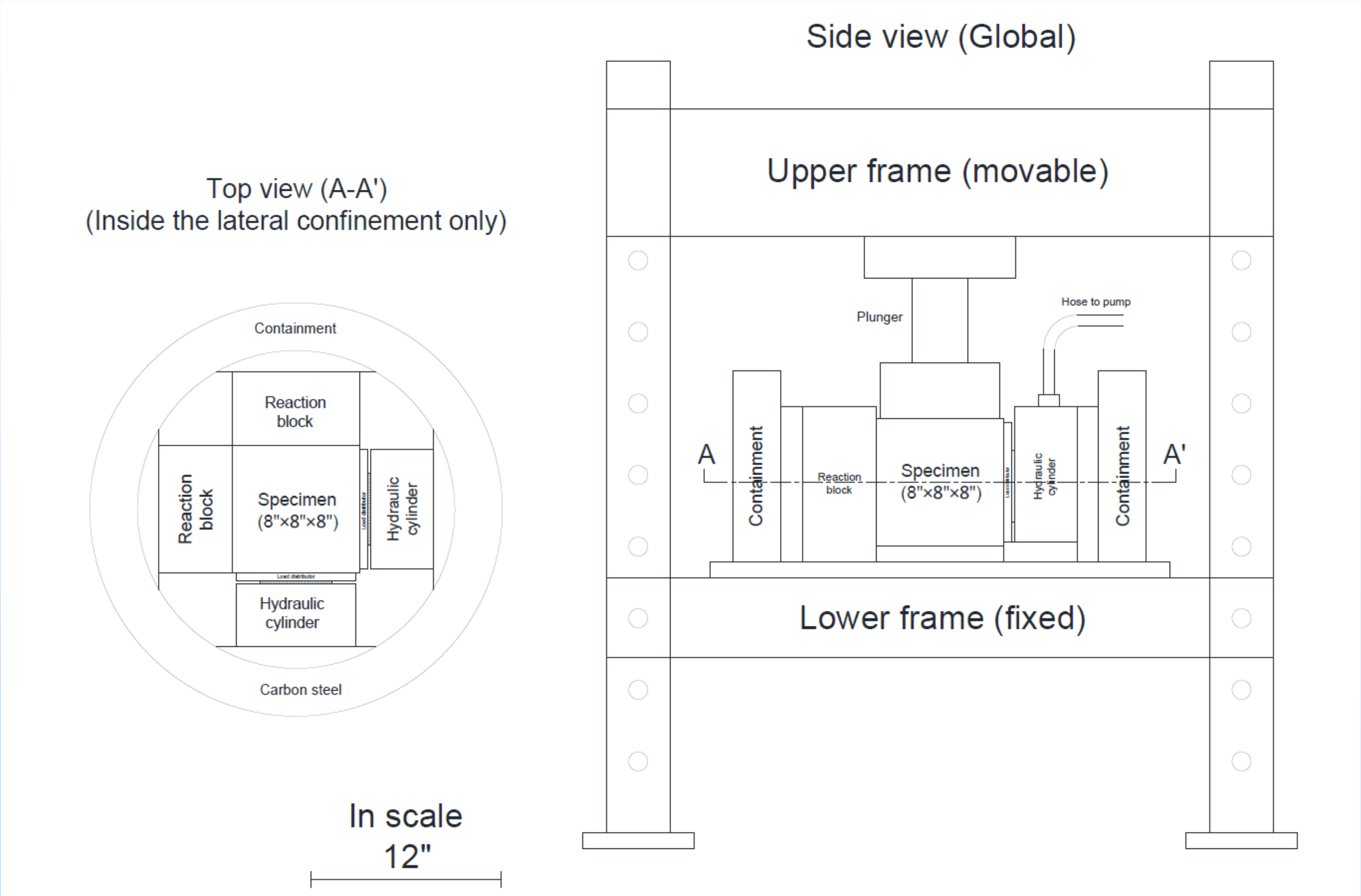
Figure 2.1. Permeability apparatus.

Triaxial Test

- Core sample is held in loading frame
- Variable axial load applied
- Confining pressure and pore pressure hydraulically generated
- Stresses, strains, pressures measured
- Axial load increased until failure
- Stress/strain data gives Young’s modulus
- Axial/radial strain data gives Poisson’s ratio

Triaxial Test – Loading Frame

Triaxial test - Schematic



Methodology, Simulations

- Start with base simulator - TOUGH2-CSM, TOUGH2-FLAC
- Formulate and code simulator modifications
- CSM simulators are run on our 32-node cluster computer (EMGCluster)
  - 16 with 16 proc./node, 24 GB memory/node
  - 16 with 24 proc./node, 32 GB memory/node

TOUGH2-FLAC

- Linkage of TOUGH2-MP, FLAC3D
- TOUGH2-MP: simulates multiphase, multicomponent fluid and heat flow in fractured and porous rock
- FLAC3D: simulates rock mechanics with thermo- and hydro-mechanical effects

TOUGH2-CSM

- Simulates fluid and heat flow and geomechanics in porous and fractured media
- Based on TOUGH2-MP parallel code
- Fluid property modules: EOS2 (H2O-CO2); ECO2N (H2O-NaCl-CO2)
- Mean Stress Formulation to simulate rock deformation (geomechanics)
- Developed to simulate CO2 sequestration in deep saline aquifers

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Expected Outcomes

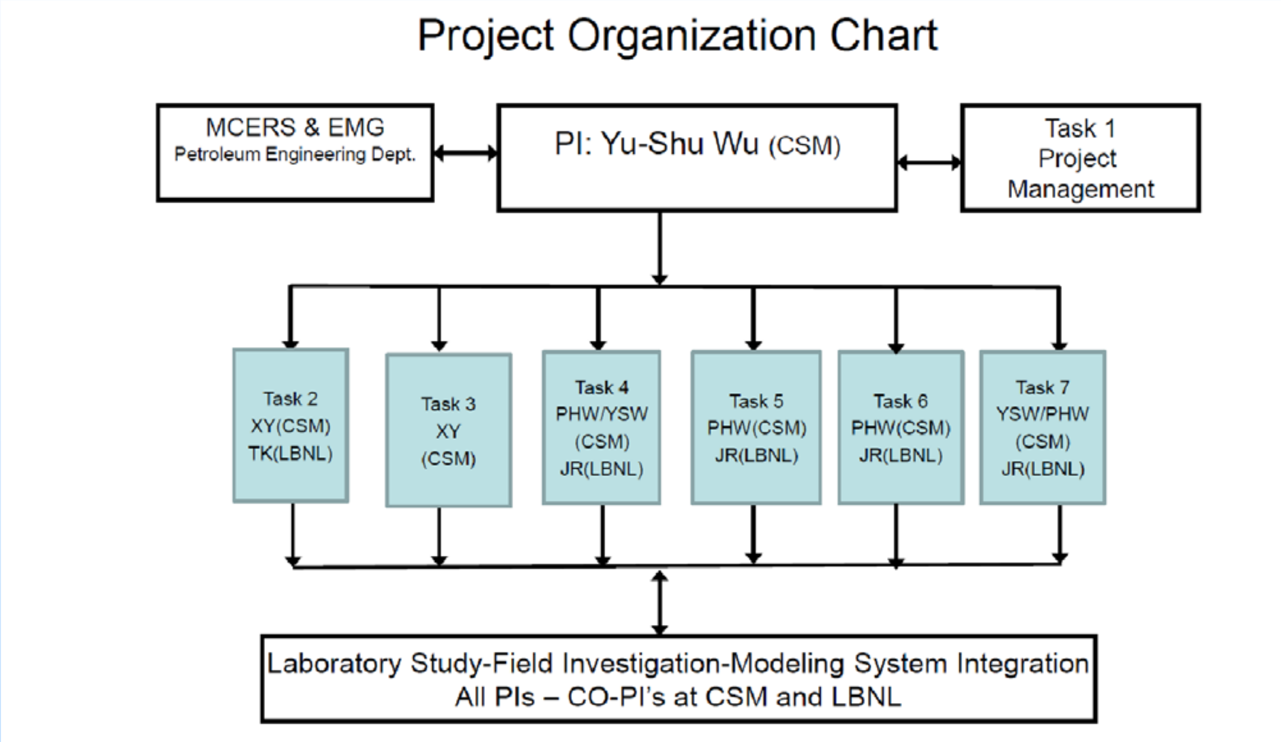
- Correlations of fracture permeability to effective stress and pore pressure for CO_2 injection
- Correlations between confining stress, fluid pressure, and fracture initialization during CO_2 injection
- Mathematical model of fracture growth and propagation for potential leakage

Expected Outcomes, continued

- Validated THM reservoir simulator with fracture initiation and propagation model, plus fracture permeability correlations

- Modeling and optimization scheme to maximize storage capacity and to identify leakage locations, times, and rates using THM reservoir simulator

Organization Chart



(Note that the chart lists only the main responsible PI or CO-PI's for each task)

YSW: Yu-Shu Wu

XY: Xiaolong Yin

PHW: Philip H. Winterfeld

JR: Jonny Rutqvist

TK: Tim Kneafsey

CSM: Colorado School of Mines

LBNL: Lawrence Berkeley National Laboratory

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Communication Plan

- CSM is the lead organization
- Project PI, Dr. Yu-Shu Wu, is also a Guest Scientist at LBNL
- He will work at LBNL several days per month over the duration of the project
- Monthly teleconferences and routine communication by phone or email will be held among the PI and CO-PI's

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Task/Subtask Breakdown

- Seven tasks
- Task 1 is Project Management

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Task 2

- 2: Laboratory studies of effects of geomechanics on CO_2 flow and transport properties in fractured rock
  - correlate effective stress to fracture effective permeability and porosity

- 2.1: Obtaining appropriate rock cores, rock characterization, and rock preparation
  - commercial sources, industrial partners, in-house
  - determine physical, mineralogical properites
  - split perpendicularly (~ two halves)

Task 2, continued

- 2.2: Permeability vs. effective stress
  - install split core in permeability apparatus
  - offset core halves to provide fracture aperture
  - X-ray core for aperture map
  - saturate core with brine
  - measure permeability versus effective stress with flowing brine

- 2.3: SC CO_2 effective permeability vs. effective stress
  - similar to 2.2, use super critical CO_2

Task 3

- 3: Laboratory studies of CO_2 and brine injection-induced fracturing
  – obtain fracture initiation condition due to CO_2 injection
  – determine dynamics of fracture propagation

- 3.1: Fracture initiation using brine
  - characterize fracture initiation pressure as function of stress, brine leakoff, pressure increase rate
  - under unconfined and triaxial stress conditions
  - X-ray CT for sample inspection for fractures, before and after experiments

Task 3, continued

- 3.2: Fracture initiation using CO_2
  - similar to 3.1, use CO_2 instead of brine
  - heat effects are considered

- 3.3: Dimensionless numbers / scaling for reservoir-scale fracture propagation
  - field-scale from laboratory-scale apparatus

Task 4

- 4: Development of CO_2 flow and geomechanics-coupled models for modeling fracturing growth
  – develop and implement approaches for modeling fracture propagation in TOUGH-CSM, TOUGH-FLAC

- 4.1: Determination of constitutive correlations for fracture initiation, and growth and propagation
  - literature review, determine modifications needed to simulate fracture initiation

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Task 4, continued

- 4.2: Modification of TOUGH2-CSM to calculate stress tensor components
- 4.3: Modification of TOUGH2-CSM to simulate fracture initiation, and growth and propagation
- 4.4: Modification of TOUGH2-FLAC to simulate fracture initiation, and growth and propagation
- 4.5: Testing and verification of TOUGH2-CSM and TOUGH-FLAC for fracture propagation modeling
  - analytical solutions, benchmark problems, comparisons to other codes

Task 5

- 5: Incorporation of CO_2 injection-enhanced property and fracture correlations/models into reservoir simulators
  - Fracture permeability versus stress
- 5.1: Modification of TOUGH2-CSM to model stress-dependent fracture permeability
- 5.2: Modification of TOUGH2-FLAC to model stress-dependent fracture permeability
- 5.3: Testing and verification of TOUGH2-CSM and TOUGH-FLAC for modeling injection-induced property changes in fractured reservoirs

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Task 6

- 6: Concept and flow-mechanics coupled model validation using field data of stress and rock deformation measurement

- 6.1: Validation of model for stress induced permeability changes in single fracture
  - Model Task 2 experiments to validate fracture permeability models

- 6.2: Verification and validation of models for fluid driven fracture propagation under triaxial stress conditions
  - Same for Task 3 experiments

Task 6, continued

- 6.3: Validation against deep fracture zone opening and surface uplift at In Salah
  - reproduce the shape and magnitude of the surface uplift

- 6.4: Application of models to a generic large-scale sequestration site
  - study pressure and temperature effects on stress
  - plus impacts on: fractured reservoir permeability and injectivity; fracture porosity on storage volume; leakage potential by a breach of the caprock through hydraulic fracturing.

Task 7

- 7: Development of modeling tools for identification of potential leakage risks
  - inverse model, coupled to software
  - maximize storage capacity, predict performance, and determine leakage location

- 7.1: Construction of an inverse modeling model and optimization scheme
  - sensitivity analysis of factors that affect CO2 leakage
  - develop an optimized inverse modeling process
  - couple the inverse model to reservoir ones

Task 7, continued

- 7.2: Validation of the coupled model
  - analytical models, cases from literature

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Deliverables / Milestones / Decision Points

- Decision points are made at end of each fiscal year of the proposed 3 year project

- The successful criteria for each task and subtask will be assessed during execution of the plan according to the milestone table

- Not anticipating any no-go decision points

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Deliverables / Milestones / Decision Points, continued

Table F-1. Project Milestones for Tasks, Completion and Verification Methods

Task/ Subtask	Milestone Title	Planned Completion Date	Verification method
1.0	Project Management Plan	9/30/14	PMP file
1.0	Project Kickoff Meeting	10/10/14	PMP file
2.1	Rock core, rock characterization, and rock preparation	9/30/2015	Tech report
2.2	Permeability vs. effective stress	9/30/2016	Tech report with data set
2.3	$scCO_2$ effective permeability vs. effective stress	9/30/2017	Final tech and data report
3.0	CO_2 injection inducing fracture experiments		
3.1	Fracture initiation using brine	9/30/2015	Tech report
3.2	Fracture initiation using CO_2	9/30/2016	Tech report
3.3	Fracture propagation	9/30/2017	Tech report
4.0	Development of CO_2 flow and geomechanics-coupled models for modeling fracturing growth	9/30/2016	Tech report, simulator and user's manual
5.0	Incorporation of CO_2 injection enhanced property and fracturing correlations/models into reservoir simulators	9/30/2016	Tech report, simulator and user's manual
6.0	Concept and flow-mechanics coupled model validation	9/30/2017	Tech report
7.0	Development and application of advanced modeling and optimization schemes and integration	9/30/2017	Tech report

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Risk Matrix

- Main risk: lack of field studies or field in-situ stress and rock deformation data for CO_2 injection and storage

- Mitigate risk:
  - extensive literature review for such data
  - communications with those experienced in those areas for updated information
  - better measurements and data collections in our laboratory studies

Proposed Schedule

	Year 1				Year 2				Year 3				Resources	Labor
Quarter	1	2	3	4	1	2	3	4	1	2	3	4		
	Task 1: Management and Planning													
Task 1: Management and Planning														
	Task 2: Development of correlations of CO_2 injection induced rock property variation by experiments													
Task 2.1: Obtaining rock core, and rock preparation														
Task 2.2: Permeability vs. effective stress														
Task 2.3: $scCO_2$ fracture permeability vs. stress														
	Task 3: Development of understanding and correlations of CO_2 injection inducing fractures by experiments													
Task 3.1: Fracture initiation using brine														
Task 3.2: Fracture initiation using CO_2														
Task 3.3: Fracture propagation														
	Task 4: Development of CO_2 flow and geomechanics-coupled models for modeling fracturing growth													
Task 4.1: constitutive correlations for fracture initiation														
Task 4.2: calculate stress tensor components														
Task 4.3: simulate fracture initiation and growth (TOUGH2-CSM)														
Task 4.4: simulate fracture initiation and growth (TOUGH2-FLAC)														
Task 4.5 verification of TOUGH2-CSM and TOUGH-FLAC for fracturing modeling														

Proposed Schedule, continued

	Task 5: Incorporation of CO_2 injection enhanced property and fracturing correlations/models into reservoir simulators											
Task 5.1: TOUGH2-CSMstress-dependent fracture permeability	■	■	■	■								
Task 5.2: TOUGH2-FLAC stress-dependent fracture permeability	■	■	■	■								
Task 5.3 Verification of TOUGH2-CSM and TOUGH-FLAC injection-induced property changes					■	■	■	■	■	■		
	Task 6: Concept and flow-mechanics coupled model validation using field data of stress and rock deformation measurement											
Task 6.1: Validation of model for stress induced permeability changes in single fracture	■	■	■	■								
Task 6.2: Validation of model for fluid driven fracture propagation					■	■	■	■				
Task 6.3: Validation against deep fracture zone opening and surface uplift at In Salah											■	■
Task 6.4: Application of models to a generic large-scale sequestration site									■	■	■	■
	Task 7: Development and application of advanced modeling and optimization schemes and integration											
Task 7.1: Inverse modeling model and optimization scheme					■	■	■	■				
Task 7.2: Validation of the coupled model:									■	■	■	■

Summary

- Research tasks have been defined and personnel assigned to them
- Work on tasks have begun

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